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## THESIS

### IMPROVED COMPUTER MODELING OF SHIP PROGRESSIVE FLOODING AS A DESIGN TOOL

by

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September 1998

Thesis Advisor:

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**IMPROVED COMPUTER MODELING OF SHIP PROGRESSIVE  
FLOODING AS A DESIGN TOOL**

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Submitted in partial fulfillment  
of the requirements for the degree of

**MASTER OF SCIENCE  
IN  
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## ABSTRACT

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When a ship suffers underwater damage, there is a rapid influx of water, followed by a period of slower progressive flooding. This results in flooding of compartments whose hull boundaries, but not interior bulkheads, are still intact. An existing computer model uses the FORTRAN computer language and formatted input files to model progressive flooding. This thesis uses MATLAB computer language and SIMULINK graphical user interface to provide a modular, expandable progressive flooding design tool.

The first part of the paper discusses the importance of the  
 research and the objectives of the study. The second part  
 describes the methodology used in the study. The third part  
 presents the results of the study. The fourth part discusses the  
 implications of the findings. The fifth part concludes the paper.

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# I. INTRODUCTION

## A. MOTIVATION

Accurate modeling of progressive flooding is essential in assessing the survivability features of a given ship. A realistic flooding and counter flooding scenario is a very complex dynamic system including complicated vessel motions, time-varying external excitation, changing hull mass and hydrodynamic properties, progressive flooding through damage openings, internal sloshing of flooded water, and de-watering control actions. Although, due to the complexity of the problem, the traditional method of approach is through large amplitude static analyses, the need for a more accurate analysis has been recognized. In order to bridge this gap, recently there has been a large amount of research focusing on dynamic stability prediction taking into consideration water-on-deck and large amplitude time-dependent motions and excitation [Ref. 1]. Equally important, however, is the development of a design methodology for incorporating elements of man/machine interface into the problem; in other words effects of decision-making and control strategies. This presents an additional level of difficulty since combinations of discrete events and continuous differential equations describe such systems. The long term goal that is initiated with this thesis is to study the development of an improved damage stability analysis and design tool, which will address the effects of control decisions and vessel dynamics in a progressive flooding scenario.

## **B. BACKGROUND**

When a ship suffers underwater damage, there is a rapid influx of flooding water, usually followed by a period of slower progressive flooding. Progressive flooding is defined as flooding which extends beyond the compartments that are open directly to the sea. This results in flooding of compartments whose hull boundaries, but not interior bulkheads, are still intact. Existing computer models at the Naval Postgraduate School utilize the FORTRAN computer language and formatted input files to model progressive flooding [Ref. 2]. Any change in model design conditions, flooding damage, or damage control abilities requires a completely new FORTRAN input file. The purpose of this thesis is to include the capabilities of the original computer progressive flooding model in a more modular and expandable format, using the user-friendly MATLAB and SIMULINK programs.

## **C. DEFINING THE MODEL**

### **1. Hole Model**

Holes can be modeled as a short-tube orifice as shown in figure 1 with a diameter (hole size) much larger than its tube length (ship's skin thickness). The flow discharge coefficient for this case is 0.816 [Ref.3: pp.42-43].

### **2. Hull Model**

The required hull characteristics are determined using the same table of offsets used by Dawson (Hull.dat) [Ref. 2: pp. 127-143] and MATLAB programs `arvol.m` and `drafts.m` to calculate the locations of center of buoyancy and center of floatation, waterplane area, and waterplane moments used in the program equations. Both Matlab

programs are included in the appendix. For the FFG-7 hull model used here the following values were calculated:

Table 1: Hull Model Characteristics

Center of Buoyancy

Xbar.....	209.9 ft aft of FP
Ybar.....	0.0 ft from CL
Zbar.....	10.52 ft from baseline

Center of Floatation

Xbar.....	227.4 ft aft of FP
Ybar.....	0.0 ft from CL

Waterplane area.....14030 ft<sup>2</sup>

Longitudinal Moment of Inertia..... $1.5883 \times 10^9$  ft<sup>4</sup>

Transverse Moment of Inertia..... $1.8148 \times 10^6$  ft<sup>4</sup>

### 3. Equilibrium Model

The added weight method [Ref.4: pp.76-79] is used within the program to determine the equilibrium condition (displacement, heel, and trim) of the hull model for any state of flooding. This method assumes hull characteristics are constant and is accurate for “small angles”. The added weight method treats flooding water as added weight and treats the hull as if it were intact. The effect of the added weight is divided into a weight, which causes the ship to immerse evenly (parallel sinkage) and moments which cause the ship to list and trim about its center of floatation. The small angle assumption assumes that the ship lists and trims about a fixed center of floatation. In reality, since the hull is not cylindrical, the location of the center of floatation will change

with changing list and trim. This method allows much simplified calculation of hull characteristics compared with the lost buoyancy method. Since the weight added is liquid water which is free to move as the ship moves (and thus does not contribute to pitch and roll resistance), a free surface correction is added to the longitudinal and transverse moments of inertia to account for the reduced resistance of the hull to pitch and roll.

#### **4. Compartment Model**

The ship compartments are modeled as rectangular boxes. Extension to more realistic shapes is one of the recommendations for further expansions to the capabilities of the program.

#### **D. SIMULINK**

The SIMULINK program provides a graphical representation of mathematical relationships and equations to enable the user to determine the response of system models. Graphical symbols and connections are used instead of numbers and mathematical symbols, allowing more intuitive use and understanding of complex mathematical relationships between system components. The SIMULINK program also allows easy modification of input parameters and import and export of data from MATLAB programs. Lastly, SIMULINK allows the user to observe system or individual component behavior during the simulation through the use of output graphs.

#### **E. OBJECTIVES**

The objective of this thesis is to develop a progressive flooding model to utilize the superior user interface and data exchange capabilities of the SIMULINK program. The



program must be able to accurately calculate flooding rates and the subsequent response of the ship. The program must also be user-friendly, easily modified and have the potential for further expansion by subsequent users. To achieve these goals the following programs were written by the author:

## **1. Programs**

### **a. Pflood.m**

Pflood.m is the main program created by the author. This program calculates the flooding and ship response caused by a hole of user-chosen size and location in the ship's hull. The flooding rate, flooded volume, heel and trim are calculated and updated each second. In addition, the user can specify the number, time of activation and size of pumps used for dewatering and the duration of their use.

### **b. Arvol.m**

Arvol.m is a MATLAB program written by the author to determine the center of buoyancy of the hull model defined by the Hull.dat data file using Simpson's rule integration techniques.

### **c. Drafts.m**

Drafts.m is a MATLAB program written by the author to determine the waterplane area, center of floatation, and second moment of inertia of the hull waterplane for a given draft.

## **2. Validation**

Program performance was validated by comparing the program output to expected ship behavior for a given flooding condition.



## II. SIMULINK PROGRAM

The schematic representation of Pflood.m is shown in Figure 1. For illustrative purposes, Pflood.m is shown in its “expanded” form. By leaving Pflood.m in expanded form, any function or variable can be observed or changed by the user. For ordinary use, the various subroutines would be grouped into subsystem blocks with only the user-defined variables and the outputs represented by discrete function blocks. Placing the program in subsystem block form has the added advantage of greatly enhancing program readability and user-friendliness. Specific details of the individual block diagram elements are included in Chapter III.



### III. PROGRAM AND SUBROUTINES

#### A. FLOW RATE THROUGH HOLE(S)

The flow through the damage, either primary or secondary, can be modeled as turbulent flow through an orifice of negligible length, or a hole. Flow rate through a hole is a function of the hole size (cross sectional area), hole shape, and pressure difference across the hole. The hole size and shape are related to the discharge coefficient,  $C_d$ . A  $C_d$  of 0.816 is used in this application in order to remain consistent with Dawson's previous computer flooding model. This number is also consistent with theoretical predictions of flow through orifices as explained in the previous chapter [Ref. 3: pp. 42-43]. The pressure difference is determined by the difference in height of the liquid on either side of the hole. The equation is

$$Q = C_d \times A \times \sqrt{2g \times (h_2 - h_1)}$$

where  $Q$  is the volumetric flow rate,  $A$  is the cross sectional area,  $C_d$  is the discharge coefficient,  $g$  is the acceleration due to gravity, and  $h_2 - h_1$  is the liquid height difference across the hole. This height difference is a function of the level of the flooding water inside the flooded tanks, as well as the draft and trim of the ship. The latter quantities will have to be calculated using the added weight method as explained in the previous chapter. The Simulink representation of the above equation is shown in Figure 2.

The program allows continuous adjustment of the values of  $h_1$  and  $h_2$  to account for increased immersion of the exterior hole and increased compartment water height.



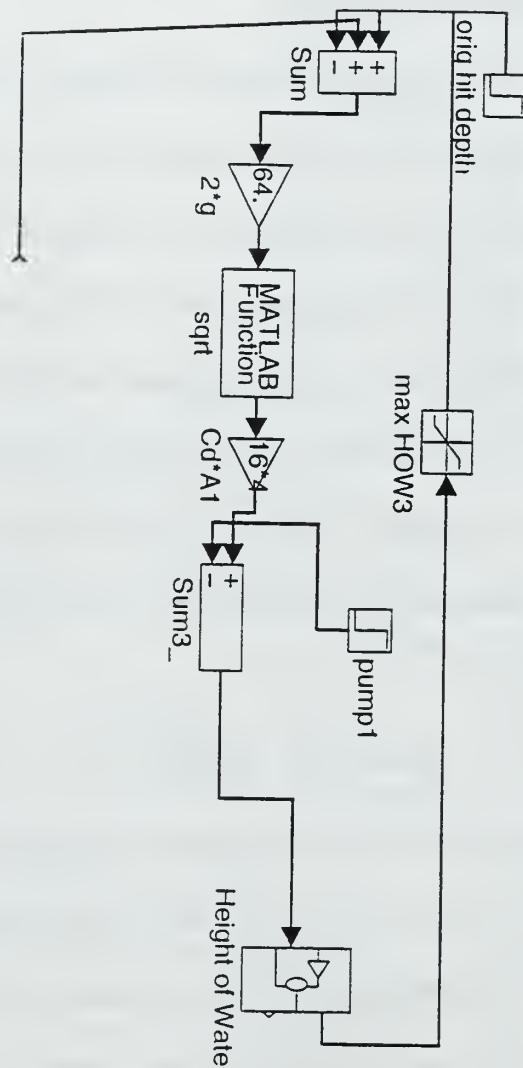


Figure 2: SIMULINK Hole Flow Symbology

## **B. NET FLOW INTO A COMPARTMENT**

Flooding water removed from the compartment by pump activation or by flow into adjacent compartments is subtracted from the water flow rate into the compartment. Two way flow due to water removal from one of two connected flooded compartments is also possible, and is accounted for by taking the square root of absolute value of the liquid height difference and then multiplying the result by the sign of the height difference. This method avoids program failure due to trying to take the square root of a negative number. This program also continuously updates the values of  $h_1$  and  $h_2$  to account for increased immersion of the exterior hole and increased compartment water height.

## **C. HEIGHT OF WATER (HOW)**

Once the net volumetric flow rate of water is known, integrating the flow rate results in the net volume of water added to the compartment. This volume, divided by the horizontal area of the compartment, and divided again by the permeability of the compartment, gives the height of water in the compartment. A saturation function ensures that the height of water in the compartment is always between zero and the maximum height of the compartment. Figure 3 shows the Simulink height of water function.

## **D. MOMENTS DUE TO ADDED WATER**

The added weight method treats the added weight as a combination of a weight which causes the ship to sink evenly (parallel sinkage) and transverse and longitudinal

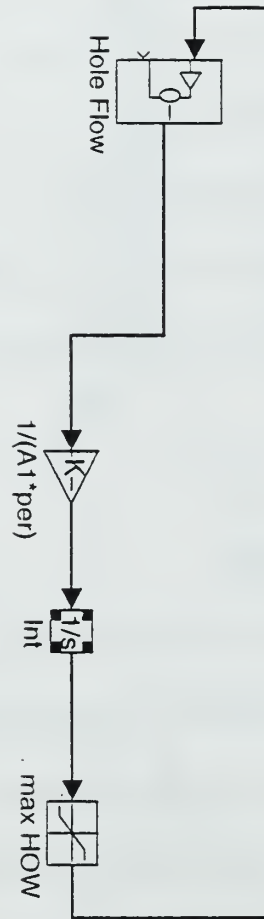


Figure 3: SIMULINK Height of Water Terminology

moments which cause the ship to heel and trim respectively. Multiplying the height of water (HOW) by the product of the weight density of the liquid ( $\rho g$ ), the compartment permeability (per), and the compartment horizontal area (A) determines the weight added to the compartment. Multiplying the added weight by the moment arm ( $Z_{trans/long}$ ) from the ship's center of floatation to the center of gravity of the added weight gives the moment about the center of floatation in the longitudinal and transverse directions. In equation form:

$$Moment = (\rho g A \times HOW \times per) \times Z_{trans / long}$$

The Simulink representation of the above equation is shown in Figure 4.

#### **E. KG (VERTICAL POSITION OF CENTER OF GRAVITY)**

KG (Vertical Position of Center of Gravity) is determined by multiplying the original weight of the ship by the original KG, adding the product of the weight of the added water and the height of the added water center of gravity above the keel, and dividing the sum by the new ship weight. The equation for KG is:

$$KG_{NEW} = (KG_{OLD} \times W_{OLD} + KG_{ADD} \times W_{ADD}) \div W_{NEW}$$

The Simulink representation is shown in Figure 5.

#### **F. VERTICAL CENTER OF BUOYANCY (KB)**

The ship's new vertical center of buoyancy (KB) is determined by multiplying the original KB by the original displacement, adding the product of the added weight and the original draft plus one half of the parallel sinkage, then dividing the product by the new



Figure 4: SIMULINK Moment Terminology



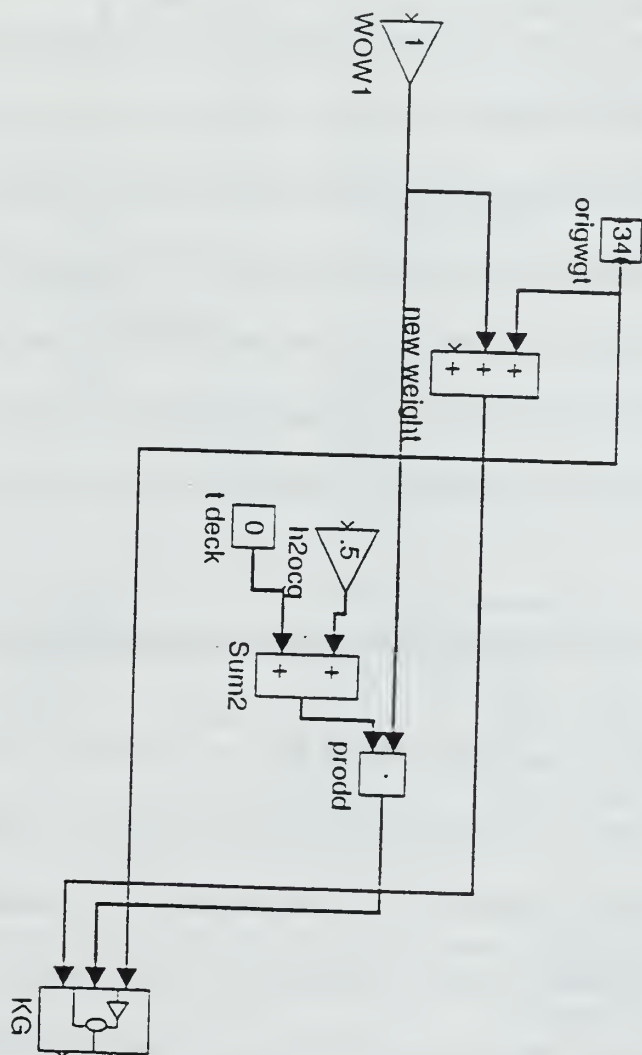


Figure 5: SIMULINK KG Terminology

weight. In equation form:

$$KB_{NEW} = (KB_{ORIG} \times W_{ORIG} + KB_{ADD} \times W_{ADD}) \div W_{NEW}$$

This is based on the assumption that the hull is effectively wall-sided, and that the vertical center of buoyancy of the newly submerged portion is located at one half the added draft.

Both of these assumptions are consistent with the small angle assumption that was mentioned in the previous chapter. If the small angle assumption is no longer true, then the true position of the center of buoyancy will have to be calculated. This can be done by employing numerical integrations and utilizing the provided table of offsets, or by interfacing the program with a standard external ship hydrostatics calculations program, such as SHCP [Ref. 2: pp. 24-25]. Such an interface is relatively straight forward since the computational environment of Matlab/Simulink already allows incorporation of external ASCII files. Figure 6 shows the Simulink representation of the KB equation.

## **G. HEIGHT OF THE METACENTER ABOVE THE CENTER OF BUOYANCY (BM)**

The height of the metacenter above the center of buoyancy (BM) is determined by the second moment of the waterplane (about the waterplane centerline or longitudinal center of floatation) divided by the hull displacement. For the added weight method, a free surface correction is made by subtracting the second moment of the flooded compartment area from the waterplane moment. Typically, free surface corrections are done for liquids when calculating the final metacentric height. In such a case, the free surface correction appears as a reduction in the metacentric height or, equivalently, an increase in the virtual center of gravity. The same effect can be observed by modifying

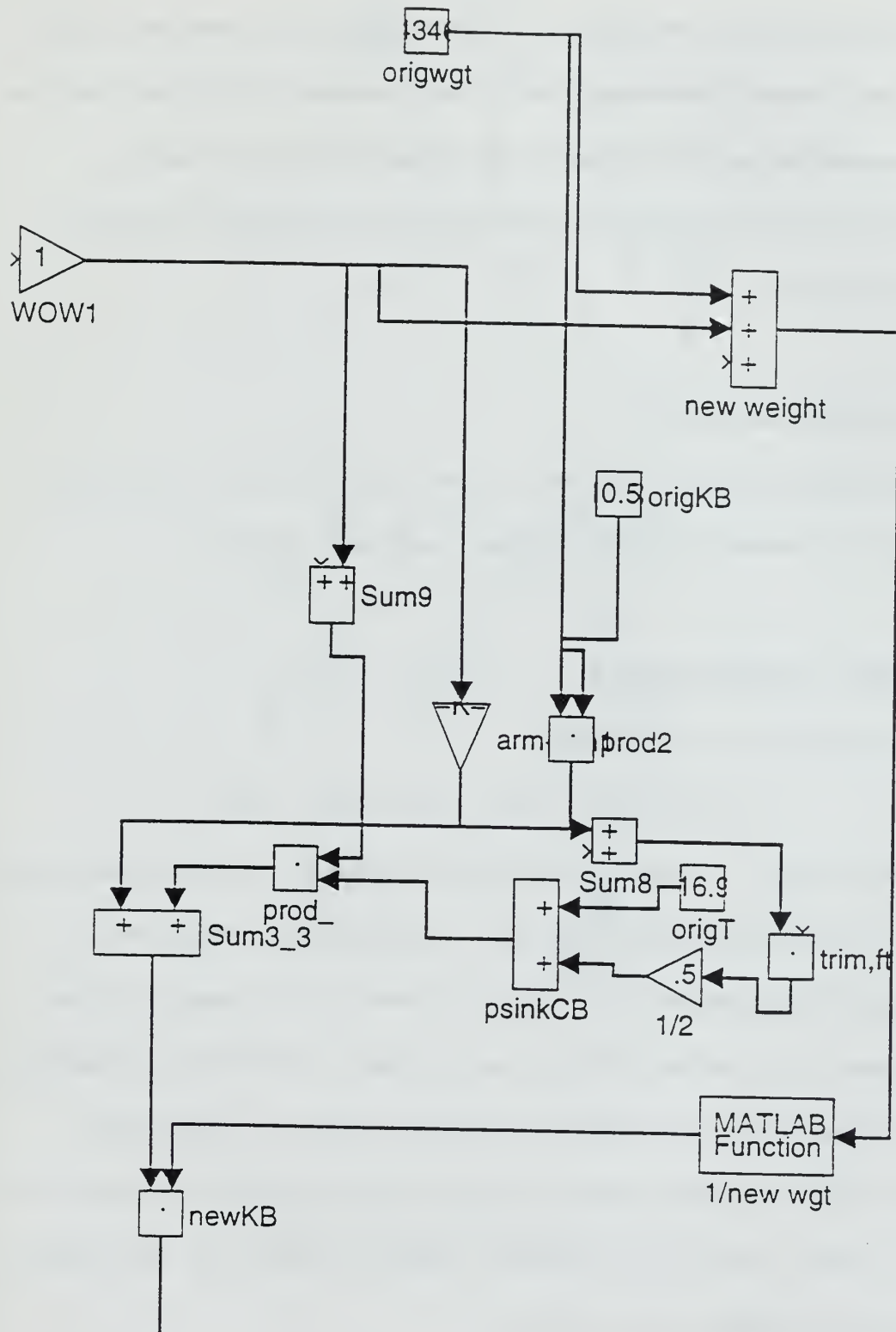


Figure 6 : SIMULINK KB Terminology

the second moment of the waterplane area in the calculation of the metacentric radius, BM. This is because the added weight in this case is seawater. With this modification in BM, the added weight method produces identical results with the lost buoyancy calculations (reference a naval architecture book). The BM Simulink terminology is shown in Figure 7.

## H. RIGHTING ARM (GM)

The righting arm (GM) is determined by  $GM = KB + BM - KG$ . This equation is graphically represented by the triple summing point shown in Figure 8.

## I. HEEL AND TRIM ANGLE

The angle of heel is determined by

$$\sin \phi = Volume \times Z_{TRANS} \div (Displacement \times GM)$$

as shown in Figure 9. The total trim is determined by dividing the total trimming moment by the moment to change trim (MCT). MCT is equal to the total weight times the longitudinal GM, divided by the ship length at the waterline. The tangent of the trim angle is equal to the total trim divided by the ship's length at the waterline. If the large angle assumption needs to be utilized, the moment to change trim will have to be imported as an external array. This is not expected to cause significant difficulties since MCT is readily available from the hydrostatic diagrams of a given ship. The Simulink trim angle terminology is shown in Figure 10.

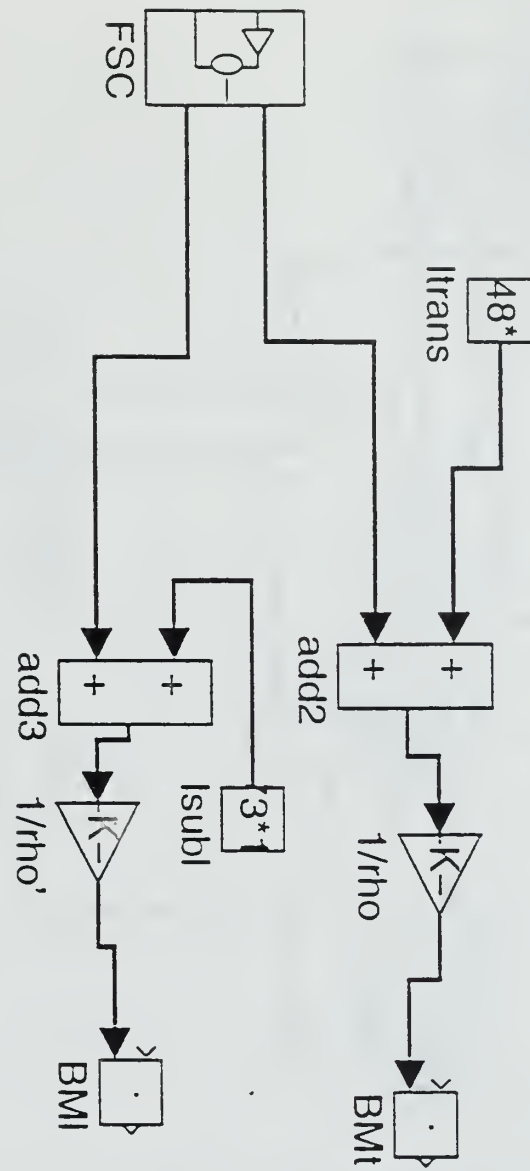


Figure 7: SIMULINK BM Terminology

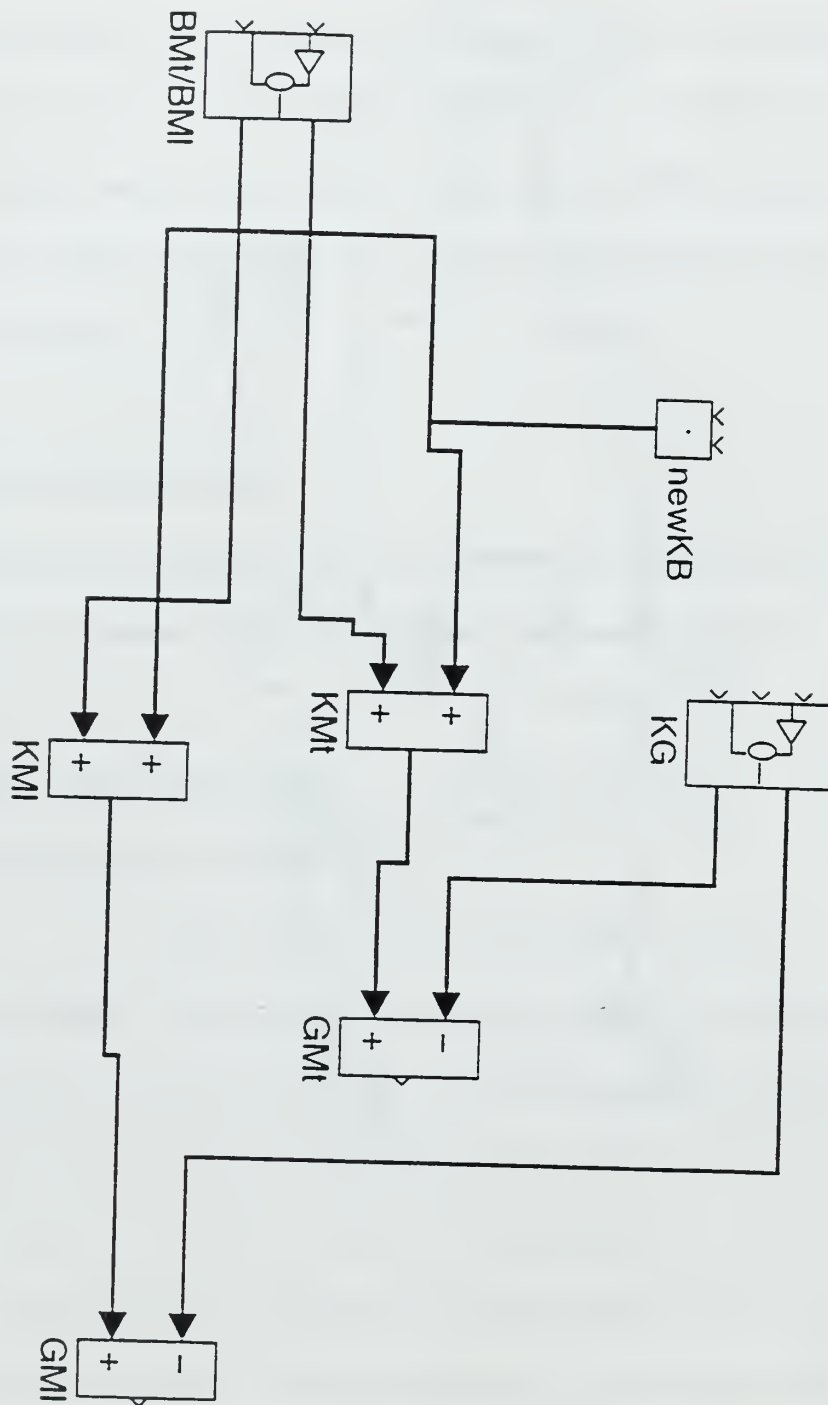


Figure 8: SIMULINK GM Terminology



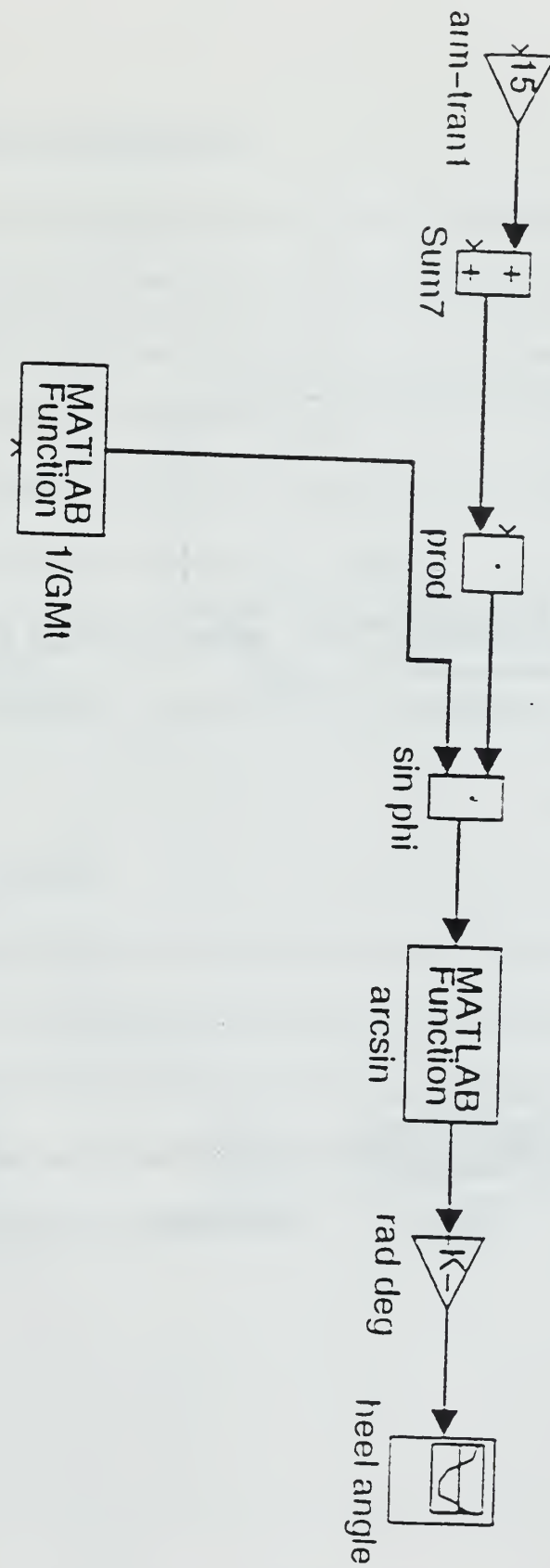


Figure 9: SIMULINK Heel Angle Terminology

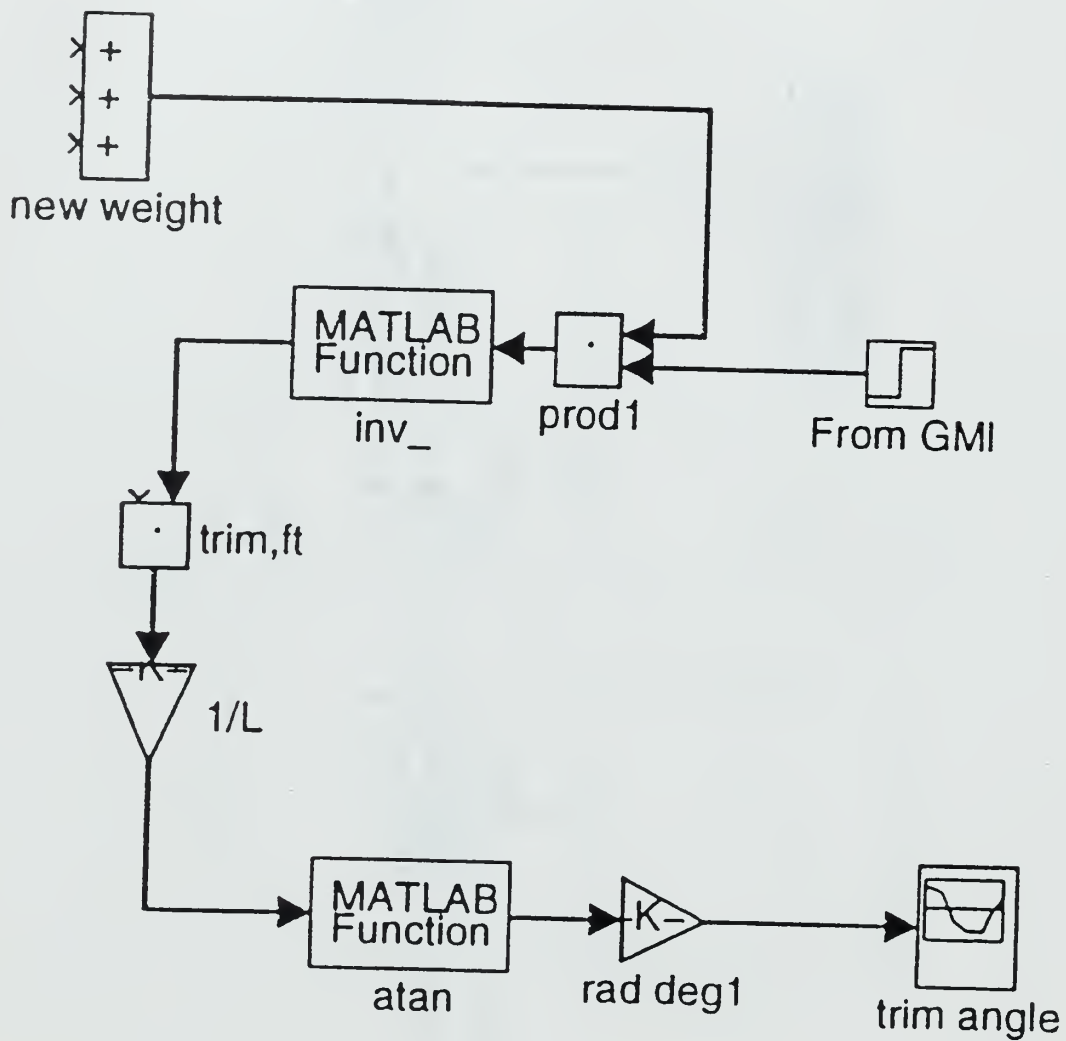


Figure 10: SIMULINK Trim Angle Terminology

## J. ADDITIONAL SUBMERGENCE

The additional submergence of the hole due to list is determined by multiplying the sine of the heel angle by the transverse distance from the transverse center of floatation to the hole. Similarly, the increased hole depth due to trim is obtained by multiplying the sine of the trim angle by the longitudinal distance to the center of floatation. The new hole depth is the sum of the original hole depth and the depth increases due to heel and trim. In algebraic form, these relations are shown by

$$h_{2NEW} = h_{2OLD} + (Z_{TRANS, hole} \times \sin \phi) + (Z_{LONG, hole} \times \sin(trim))$$

and in graphical form they are represented by the diagram of Figure 11.

## K. PROGRAM USAGE

To use Pflood.m, the user needs only select “simulation” from the SIMULINK menu, then select “start”. Modifications to the simulation parameters or the program are easily accomplished by “double-clicking” on the symbol of interest. Additionally, SIMULINK allows the user to easily add output displays in order to observe the behavior of any desired variable during the simulation.

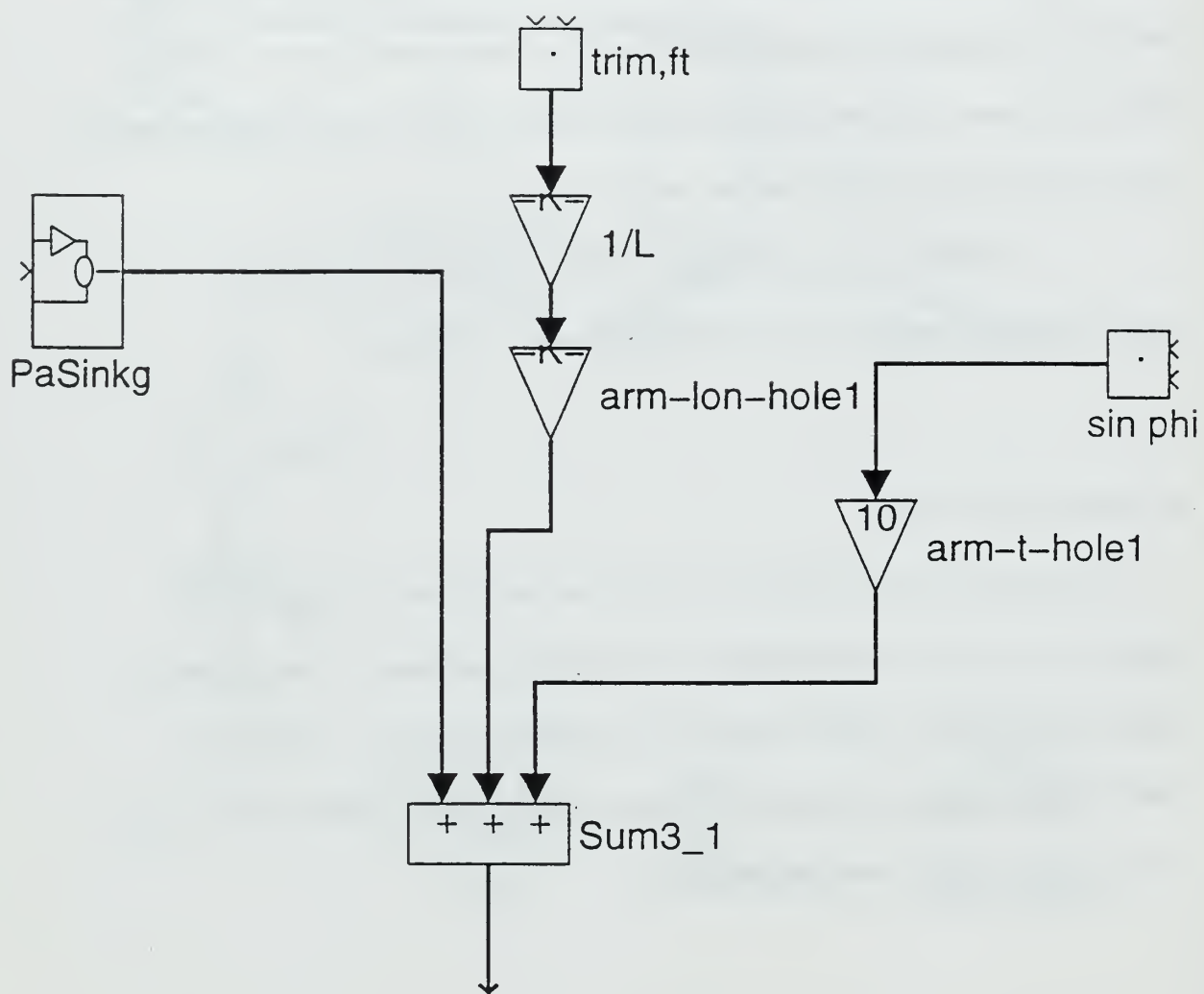


Figure 11: SIMULINK Hole Submergence Terminology

#### IV. RESULTS

Results for a test case consisting of a compartment with a 4 square foot hull penetration (compartment 1) and a 4 square inch watertight bulkhead penetration (compartment 2). Pumps were activated at 10 minutes (600 seconds) which completely dewatered compartment 1 in order to test the ability of the program to account for backflow through holes. As shown in figure 12, the four square foot hull penetration completely floods compartment 1 essentially instantly. Activating the pumps dewater compartment 1, instantly removing the water entering through the hull penetration. Similar results could have been achieved by changing the characteristics of the hull penetration to simulate hull repairs.

Figure 13 illustrates how the program accurately predicts backflow into compartment 1 from compartment 2, which had no pumps assigned. A saturation function ensures that backflow from compartment 2 will stop when compartment 2 water height drops to the level of the bulkhead penetration.

The predicted trim response of the ship is shown in Figure 14. The ship initially trims as a result of the rapid flooding of compartment 1, then gradually increases its trim angle as compartment 2 floods. The instant dewatering of compartment 1 then causes the trim angle to decrease, followed by further trim angle reduction as compartment 2 is dewatered. Without altering the pump or hole configuration, the ship will assume a steady trim angle corresponding to compartment 2 flooded up to the height of the bulkhead penetration.

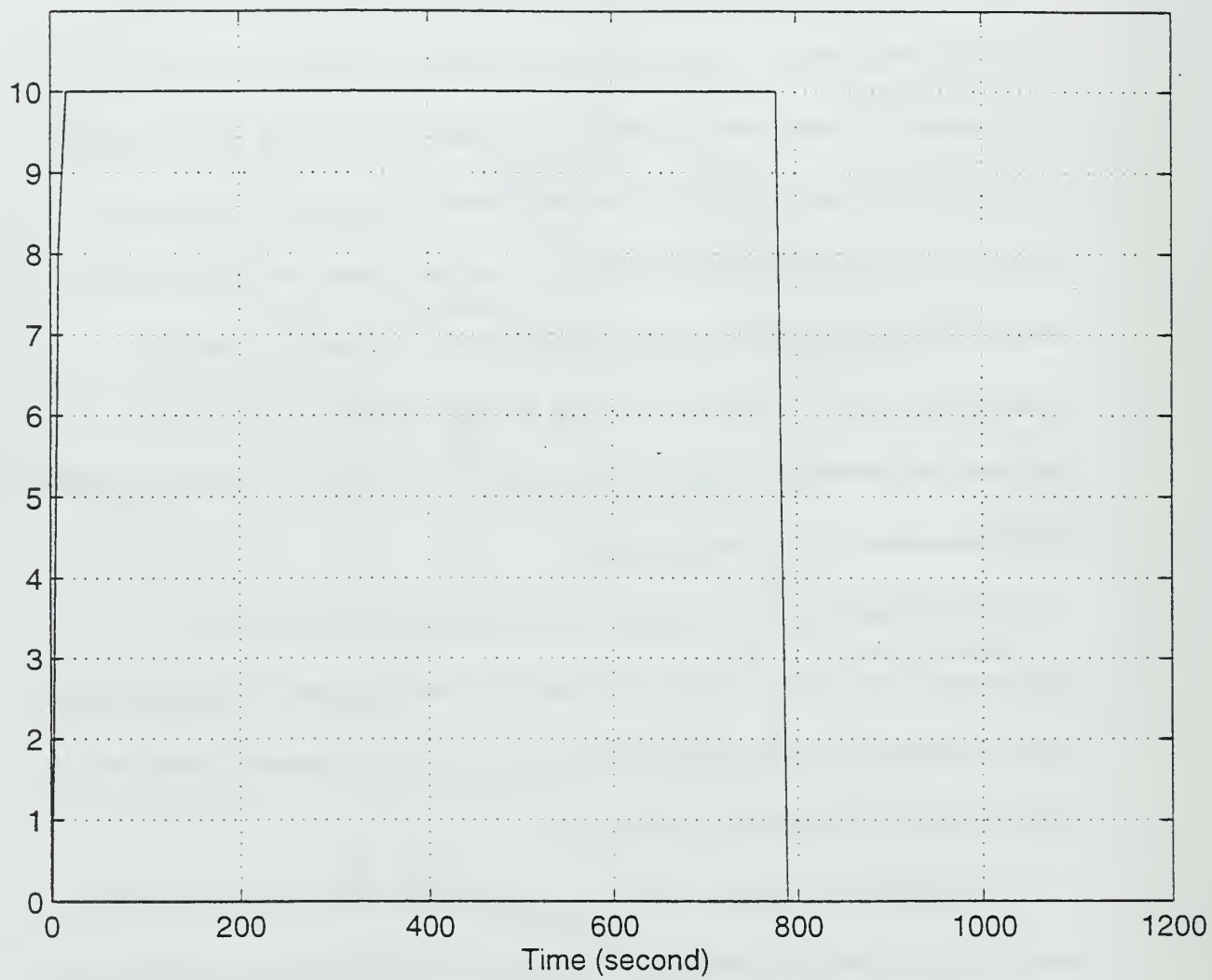


Figure 12: Height of Water in Compartment 1

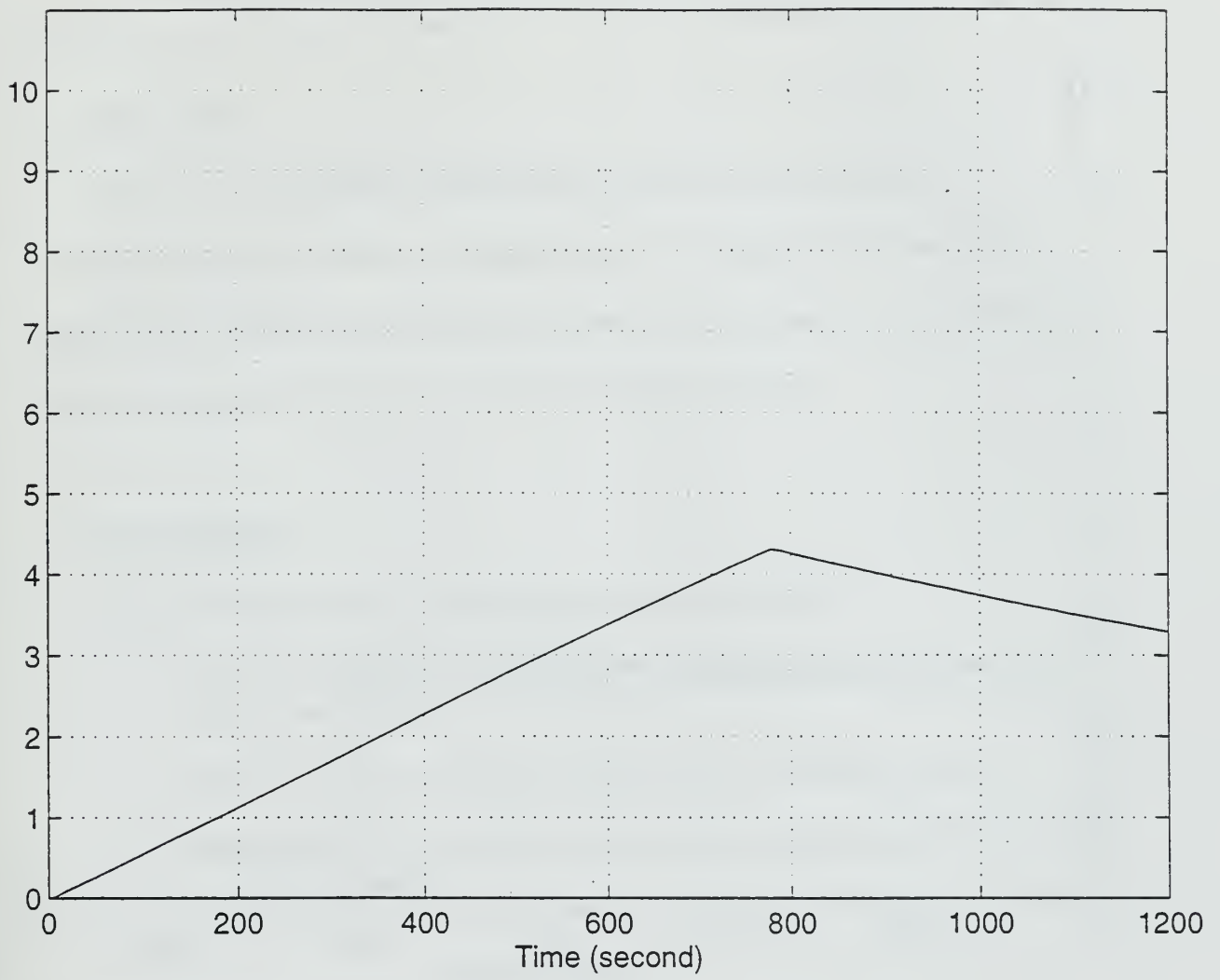


Figure 13: Height of Water in Compartment 2



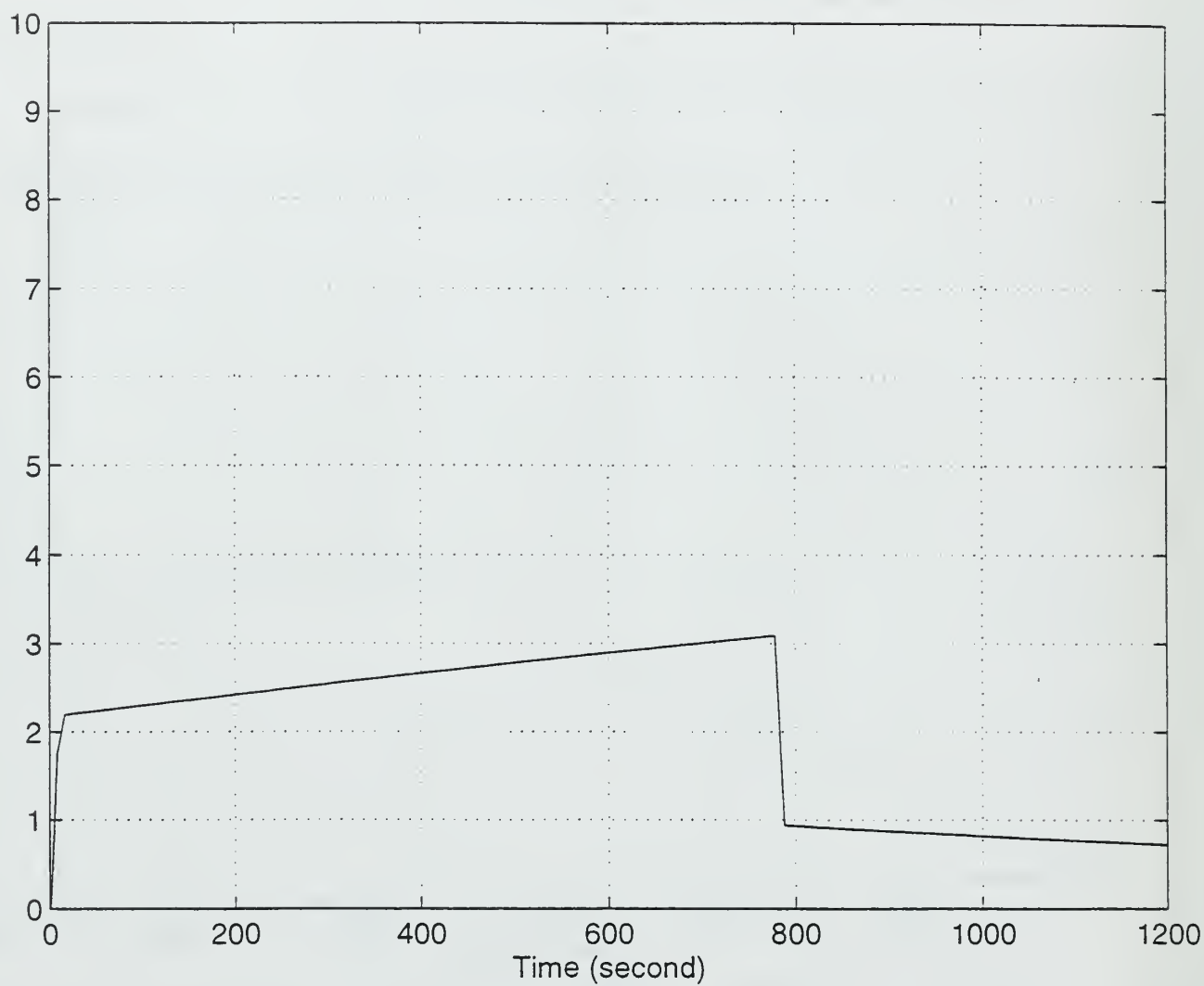


Figure 14: Ship Trim Response

## **V. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS**

### **A. DISCUSSION**

This thesis has successfully developed the foundation for a modular and expandable progressive flooding computer model. The computer model accurately predicts the quasi-static ship response to progressive flooding and is easily modified by the user to explore ship response to any desired damage situations.

### **B. CONCLUSIONS**

Based on the above results, the following conclusions are drawn:

1. Pflood.m is an effective design tool for modeling and studying the effects of progressive flooding.
2. Pflood.m is easily modified to model virtually any damage scenario.
3. Pflood.m can be expanded to include different ship progressive flooding and equilibrium models.

### **C. RECOMMENDATIONS**

The following items are recommended to further expand Pflood.m and enhance its utility as a design tool:

1. Incorporate a hull characteristics look-up table into the Pflood.m program to expand the ship response modeling ability beyond “small angles” of heel and trim and non-rectangular compartments.
2. Explore the effect of pump configuration on dewatering effectiveness and ship response.



## APPENDIX A: HULL.DAT

```
-.98 .203 34.011
-.98 1.0097 37.035
-.98 2.09 40.059
-.98 2.30593 40.636
-.98 2.525 41.213
-.49 .204 24.201
-.49 1.0381 28.1305
-.49 2.2 32.06
-.49 3.60937 36.059
-.49 5.199 40.058
-.49 5.26214 40.2255
-.49 5.325 40.393
.196 .207 10.687
.196 .4439 12.3765
.196 .741 14.066
.196 1.2739 17.065
.196 1.881 20.064
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.98 1.621 6.065
.98 1.811 7.065
.98 2.10725 8.565
.98 2.381 10.065
.98 2.7609 12.0645
.98 3.166 14.064
.98 3.38543 15.0635
.98 3.621 16.063
.98 4.70985 20.0605
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1.569 .73779 .288
1.569 .98 .545
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20.294 6.005 21.711



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20.392 14.012 25.743  
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20.49 15.086 28.4075  
20.49 16.131 28.782  
20.49 16.506 28.8625  
20.49 16.88 28.943

## APPENDIX B. ARVOL.M

```

%          arvol.m
%          by Russell wright
%          calculates station areas and center o' bouyancy
%          for T =16.9 ft

load hull1.dat
a=zeros(41,3);
zz=16.9
for i=1:41

    beg=23*(i-1)+1;
    endd=23*i;
    a(i,1)=hull1(beg);
    z=hull1(beg:endd,3);
    if z(1) > zz
        a(i,3)=0;a(i,2)=1;
    else
%   y=hull1(beg:endd,2);

        zp=hull1(beg:endd,3);
        z=zp(1):(16.9-zp(1))/22:16.9;
        yy=hull1(beg:endd,2);
        y=spline(zp,yy,z);
        h=z(2)-z(1);
        hhh(i)=h;
        four = 0.0;fr=0;
        two=0.0;to=0;

        for j= 1:11
            four=four+y(2*j);
            fr=fr+z(2*j)*y(2*j);
        end

        for k=1:10
            two= two+y(2*k+1);
            to=to+y(2*k+1)*z(2*k+1);
        end

        % calculate station area using simpson's rule:
        a(i,2)=2*(y(1)+4*four+2*two+y(23))*h/3;
        % calculate station centroid (z bar) using simpson's rule:
        a(i,3)=2*(y(1)*z(1)+4*fr+2*to+y(23)*z(23))*h/(3*a(i,2));

    end

end

aa=zeros(101,3);
hh=((a(37,1)-a(3,1))/100);
aa(:,1)=(a(3,1):hh:a(37,1))';
aa(:,2)=spline(a(3:37,1),a(3:37,2),aa(:,1));
aa(:,3)=spline(a(3:37,1),a(3:37,3),aa(:,1));

fore=0;too=0;fre=0;tw=0;fo=0;tu=0;
for i=1:50
    fore=fore+aa(2*i,2);
    fre=fre+aa(2*i,2)*aa(2*i,3);
    fo=fo+aa(2*i,2)*aa(2*i,1);
end

for i=1:49
    too=too+aa(2*i+1,2);

```

```

tw=tw+aa(2*i+1,2)*aa(2*i+1,3);
tu=tu+aa(2*i+1,2)*aa(2*i+1,1);
end

vol=(hh/3)*(aa(1,2)+4*fore+2*too+aa(101,2));
zbar=(aa(1,2)*aa(1,3)+4*fre+2*tw+aa(101,2)*aa(101,3))*hh/(3*vol)
xbar=(aa(1,2)*aa(1,1)+4*fo+2*tu+aa(101,2)*aa(101,1))*hh/(3*vol)

```

## APPENDIX C. DRAFTS.M

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%                               drafts2.m
%                               by russell wright
%                               calculates wp points for a given draft
%

load hull1.dat
ind=0;
yincl=zeros(41,3);
zz=16.9;

zincl=zz
zinc2=zz
for i=1:41
    i
        beg=23*(i-1)+1;
        endd=23*i;
        wpla(i,1)=hull1(beg,1);
        z=hull1(beg:endd,3);
        y=hull1(beg:endd,2);

        wpla(i,2)=interp1(z,y,zz,'spline');
        if z(1) > zz
            wpla(i,2)=0;
            yincl(i,2)=0;
            yincl(i,3)=0;
            wpla(i,1)=0;
        end

        yincl(i,1)=hull1(beg,1);
        yincl(i,2)=interp1(z,y,zincl,'spline');
        if yincl(i,2) < 0.0
            yincl(i,2) = 0.0;
        end
        yincl(i,3)=zz;

        if wpla(i,2)==0
            yincl(i,2)=0;
            yincl(i,3)=0;
        end
    end

    yincl=yincl(3:37,:);

    xx=yincl(:,1);
    x=yincl(1,1):(yincl(35,1)-yincl(1,1))/34:yincl(35,1);
    yy=yincl(:,2);
    y=spline(xx,yy,x);

    h=x(2)-x(1);
    hhh(i)=h;
    four = 0.0; fr=0;
    two=0.0; to=0;

    for j= 1:17
        four=four+y(2*j);
        fr=fr+x(2*j)*y(2*j);
    end
end

```

```

end

for k=1:16
    two= two+y(2*k+1);
    to=to+y(2*k+1)*x(2*k+1);
end

% calculate wp 1/2 area using simpson's rule:
a2=2*(y(1)+4*four+2*two+y(35))*h/3;
% calculate wp centroid (x bar) using simpson's rule:
xbar=2*(y(1)*x(1)+4*fr+2*to+y(35)*x(35))*h/(3*a2)

% calculate long. moment o' inertia about xbar

fr=0;
to=0;

for j= 1:17
    fr=fr+(x(2*j)^2)*y(2*j);
end

for k=1:16
    to=to+y(2*k+1)*(x(2*k+1)^2);
end

io=2*(y(1)*x(1)*x(1)+4*fr+2*to+y(35)*(x(35)^2))*h/3;
isubl=io-a2*xbar^2
% calculate trans moment o' inertia

fr=0;
to=0;

for j= 1:17
    fr=fr+(y(2*j)^3);
end

for k=1:16
    to=to+(y(2*k+1)^3);
end

isubt=2*((y(1)^3)+4*fr+2*to+(y(35)^3))*h/9;

```

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